

Is the nonmonotonic behavior in the cross section of ϕ photoproduction near threshold a signature of a resonance?

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Abstract

We study whether the nonmonotonic behavior found in the differential cross section of the ϕ -meson photoproduction near threshold can be described by a resonance. Namely, we add a resonance to a model consisting of Pomeron and (π, η) exchange by fiat and see if, with a suitable assignment of spin and parity, mass and width, as well as the coupling constants, one would be able to obtain a good description to all the data reported by the LEPS collaboration in the low-energy region. The resonant contribution is evaluated by using an effective Lagrangian approach. We find that, with the assumption of a $J^P = 3/2^-$ resonance with mass of 2.10 ± 0.03 GeV and width of 0.465 ± 0.141 GeV, LEPS data can indeed be well described. The ratio of the helicity amplitudes $A_{\frac{1}{2}}/A_{\frac{3}{2}}$ calculated from the resulting coupling constants differs in sign from that of the known $D_{13}(2080)$. We further find that the addition of this postulated resonance can substantially improve the agreement between the existing theoretical predictions and the recent ω photoproduction data if a large value of the OZI evading parameter $x_{\text{OZI}} = 12$ is assumed for the resonance.

Keywords: Photoproduction, ϕ meson, nucleon resonance, Pomeron

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A well-established feature in the ϕ -meson photoproduction reaction at high energies is that it is dominated by the diffractive processes, which are conveniently described by the t -channel Pomeron (P) exchange [1, 2]. In the low-energy region, the nondiffractive processes of the pseudoscalar (π, η) -meson exchange are known to contribute [1]. In addition, many other processes, including nucleon and nucleon-resonance exchanges, second Pomeron exchange, t -channel scalar meson and glueball exchanges, and $s\bar{s}$ -cluster knockout have also been extensively studied [3, 4, 5, 6, 7, 8, 9]. However, no definite conclusion has been reached because of the limited experimental data.

Recently, a local maximum in the differential cross sections of ϕ photoproduction on protons at forward angles at around $E_\gamma \sim 2.0$ GeV, has been observed by the LEPS collaboration [10]. Models which consist of t -channel exchanges [3, 4, 5, 6, 7, 8, 9] have not been able to account for such a nonmonotonic behavior.

Typically, local maxima in the cross sections are often associated with resonances. Effects of the resonances in s - and u -channels up to mass 2 GeV have been investigated in Refs. [9, 11]. Ref. [11] used a constituent quark model with $\text{SU}(6) \otimes \text{O}(3)$ symmetry and included explicitly excited resonances with quantum numbers $n \leq 2$, while Ref. [9] considered all the known 12 resonances below 2 GeV listed in Particle Data Group [12],

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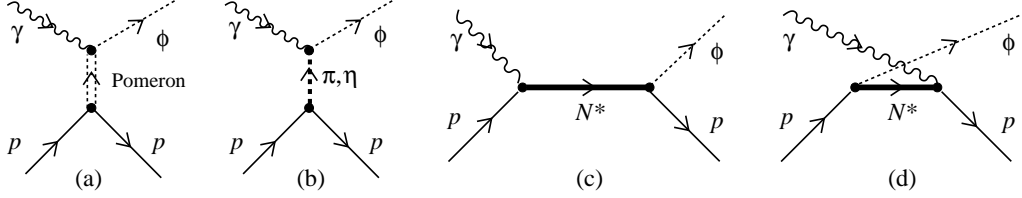


Figure 1: (a) Pomeron-exchange, (b) (π, η) -exchange, and (c) s - and u -channel N^* -exchange diagrams for $\gamma p \rightarrow \phi p$ reaction.

with coupling constants determined by the available data [13, 14] at large momentum transfers. The resonances are found to play non-negligible role, especially in polarization observables. However, no local maximum as observed in Ref. [10] was obtained.

In this Letter, we study whether the nonmonotonic behavior found in Ref. [10] can be described by a resonance. Namely, we will add a resonance to a model consisting of Pomeron and (π, η) exchange by fiat and see if, with a suitable assignment of spin and parity, mass and width, as well as the coupling constants, one would be able to obtain a good description of all the data reported by the LEPS collaboration, which include the angular and energy dependence of the differential cross section and decay angular distributions in the Gottfried-Jackson frame, in the low-energy region from threshold to $E_\gamma = 2.37$ GeV. Since the local maximum appears quite close to the threshold, we will investigate, as a first step, the possibility of the spin of the resonance being either $1/2$ or $3/2$. Similar analysis was carried out in a coupled-channel model [15]. However, the analysis was marred by a confusion in the phase of the Pomeron-exchange amplitude [16].

We first define the kinematical variables k , p_i , q , and p_f as the four-momenta of the incoming photon, initial proton, outgoing ϕ -meson, and final proton, respectively; and $s = (k + p_i)^2$, $t = (q - k)^2$, and $u = (p_f - k)^2$. The full amplitude in our model consists of Pomeron-exchange, t -channel (π, η) -exchange, and the s - and u -channel N^* -exchange amplitudes. The Pomeron-exchange amplitude can be expressed as [8, 9],

$$\begin{aligned} \mathcal{M}_P &= -\bar{u}(p_f, \lambda_{N'}) M(s, t) \Gamma^{\mu\nu} u(p_i, \lambda_N) \\ &\times \varepsilon_\mu^*(q, \lambda_\phi) \varepsilon_\nu(k, \lambda_\gamma), \end{aligned} \quad (1)$$

where $\varepsilon_\mu(q, \lambda_\phi)$ and $\varepsilon_\nu(k, \lambda_\gamma)$ are the polarization vectors of the ϕ -meson and photon with helicities λ_ϕ and λ_γ , respectively; and $u(p, \lambda_N)$ the Dirac spinor of the nucleon with momentum p and helicity λ_N . The explicit form for the transition operator $\Gamma^{\mu\nu}$ can be found in Refs. [8, 9] and the scalar function $M(s, t)$ is given by the Reggeon parametrization,

$$\begin{aligned} M(s, t) &= C_P F_1(t) F_2(t) \frac{1}{s} \left(\frac{s - s_{th}}{4} \right)^{\alpha_P(t)} \\ &\times \exp[-i\pi\alpha_P(t)/2], \end{aligned} \quad (2)$$

where we introduce an additional threshold factor s_{th} as also done in Refs. [5, 6, 8] to adjust the shape of the energy dependence of the Pomeron amplitude near the threshold. Also, $F_1(t)$ and $F_2(t)$ are the isoscalar electromagnetic form factor of the nucleon and the

form factor of $\gamma\phi P$ coupling, respectively, and are taken to be of the form given in Refs. [2, 8]. As in [8], we take $\alpha_P(t) = 1.08 + 0.25t$, $\mu_0^2 = 1.1 \text{ GeV}^2$, and $C_P = 3.65$ which is obtained by fitting to the total cross sections data at high energy. We choose $s_{th} = 1.3 \text{ GeV}^2$ by matching the forward differential cross sections data at around $E_\gamma = 6 \text{ GeV}$ [17].

The contribution of the t -channel (π, η) exchange to the ϕ photoproduction is rather well understood. We use the same set of parameters for the pseudoscalar-exchange amplitude as adopted in Ref. [9] except, in their notation, $g_{\eta NN} = 1.12$ [18] and $\Lambda_{\pi(\eta)} = 1.2 \text{ GeV}$, the cutoff in the form factor.

We will consider the cases where the spin of the resonance is either $1/2$ or $3/2$. The interaction Lagrangian densities which describe the coupling of spin- $1/2$ and $3/2$ particles to γN and ϕN , can in general be written as [18, 19, 20],

$$\begin{aligned} \mathcal{L}_{\phi NN^*}^{1/2^\pm} &= g_{\phi NN^*}^{(1)} \bar{\psi}_N \Gamma^\pm \gamma^\mu \psi_{N^*} \phi_\mu \\ &+ g_{\phi NN^*}^{(2)} \bar{\psi}_N \Gamma^\pm \sigma_{\mu\nu} F^{\mu\nu} \psi_{N^*}, \end{aligned} \quad (3)$$

$$\begin{aligned} \mathcal{L}_{\phi NN^*}^{3/2^\pm} &= i g_{\phi NN^*}^{(1)} \bar{\psi}_N \Gamma^\pm (\partial^\mu \psi_{N^*}^\nu) \tilde{G}_{\mu\nu} \\ &+ g_{\phi NN^*}^{(2)} \bar{\psi}_N \Gamma^\pm \gamma^5 (\partial^\mu \psi_{N^*}^\nu) G_{\mu\nu} \\ &+ i g_{\phi NN^*}^{(3)} \bar{\psi}_N \Gamma^\pm \gamma^5 \gamma_\alpha \\ &\times (\partial^\alpha \psi_{N^*}^\nu - \partial^\nu \psi_{N^*}^\alpha) (\partial^\mu G_{\mu\nu}), \end{aligned} \quad (4)$$

where $G_{\mu\nu} = \partial_\mu \phi_\nu - \partial_\nu \phi_\mu$ represents the ϕ -meson field tensor and $\tilde{G}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\alpha\beta} G^{\alpha\beta}$ with $\epsilon^{0123} = +1$. The operator Γ^\pm are given by $\Gamma^+ = 1$ and $\Gamma^- = \gamma_5$, depending on the parity of the resonance N^* . For the γNN^* vertices, one simply changes $g_{\phi NN^*} \rightarrow e g_{\gamma NN^*}$ and $\phi_\mu \rightarrow A_\mu$. However, current conservation consideration fixes $g_{\gamma NN^*}^{(1)}$ for $J^P = 1/2^\pm$ resonances to be zero. In addition, the term proportional to $g_{\gamma NN^*}^{(3)}$ in the Lagrangian densities of Eq. (4) vanishes in the case of real photon. The form factor for the vertices used in the s - and u -channel diagrams, $F_{N^*}(p^2)$, is taken as $F_{N^*}(p^2) = \Lambda^4 / [\Lambda^4 + (p^2 - M_{N^*}^2)^2]$ [21, 22], with Λ the cutoff parameter for the virtual N^* . We choose $\Lambda = 1.2 \text{ GeV}$ for all resonances. The effect of the width is taken into account in a Breit-Wigner form by replacing the usual denominator $p^2 - M_{N^*}^2 \rightarrow p^2 - M_{N^*}^2 + i M_{N^*} \Gamma_{N^*}$, with Γ_{N^*} is the total decay width of N^* . Since $u < 0$, we take $\Gamma_{N^*} = 0 \text{ MeV}$ for the u -channel propagator.

With the interaction Lagrangian densities given in Eqs. (3,4), it is straightforward to write down the invariant amplitudes of the s - and u -channel exchange diagrams of the corresponding N^* . In tree-level approximation, only the products like $e g_{\gamma NN^*} g_{\phi NN^*}$, enter in the invariant amplitudes. They are determined with the use of MINUIT, by fitting to the experimental data [10], including differential cross section at forward angle as a function of photon energy and differential cross section as a function of t at different photon energies, as well as to five decay angular distributions at two photon energies.

We find that with the assignments of $J^P = 1/2^\pm$ to the resonance, it is not possible to produce the nonmonotonic behavior near threshold, in contrast to the finding of Refs. [15, 16].

For the assignments of $J^P = 3/2^\pm$, we find that both parities can describe the differential cross section at forward angle well and can also describe other observables

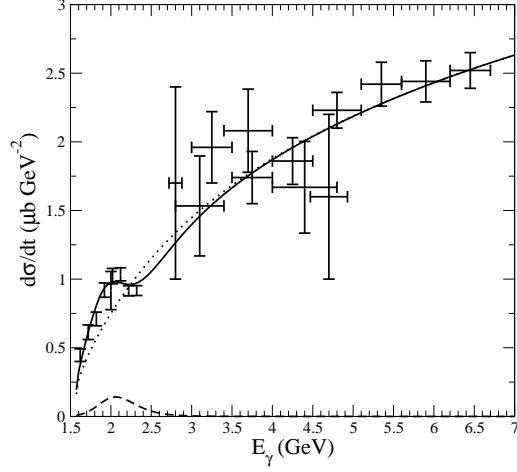


Figure 2: Differential cross section of $\gamma p \rightarrow \phi p$ at forward direction as a function of photon energy E_γ . The dotted, dashed, and solid lines denote contributions from nonresonant, resonance with $J^P = 3/2^-$, and their sum, respectively. Data are from Refs. [10, 17].

with comparable quality. The resulting χ^2/N , and (mass, width) in unit of GeV, for the case of $3/2^+$ and $3/2^-$ are 1.066 and $(2.05 \pm 0.06, 0.450 \pm 0.111)$, and 0.983 and $(2.10 \pm 0.03, 0.465 \pm 0.141)$, respectively. This leads us to the problem of determining the parity of the resonance.

To resolve this question, we perform a stability check against changes in Pomeron contribution, whose low-energy behavior is not yet fully understood. It turns out that the extracted properties of the resonances are more sensitive with respect to the variation in the Pomeron parameters if the positive parity is chosen. Therefore, we prefer the choice of $J^P = 3/2^-$. The coupling constants and the extracted mass and width of the $J^P = 3/2^-$ resonance are given in Table 1.

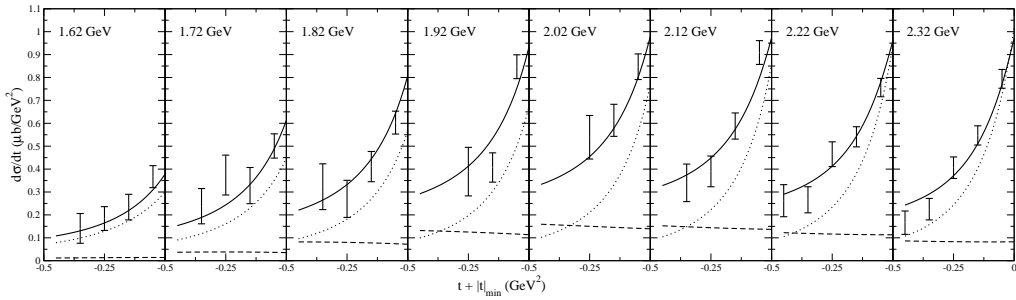


Figure 3: Differential cross sections of $\gamma p \rightarrow \phi p$ as a function of t at eight different photon LAB energies. Data is taken from Ref. [10]. The notation is the same as in Fig. 2.

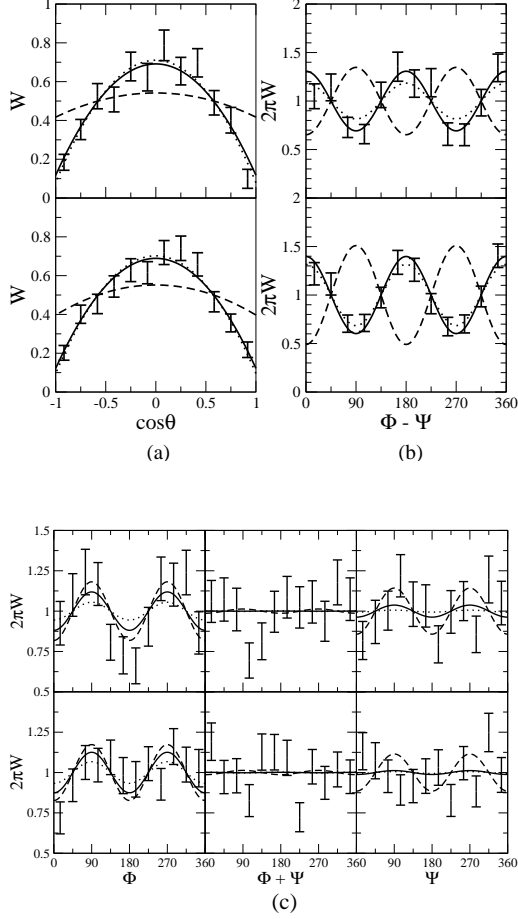


Figure 4: Our results obtained with $J^P = 3/2^-$ resonance: (a) decay angular distributions $W(\cos\theta)$ (b) $W(\Phi - \Psi)$, and (c) $W(\Phi)$, $W(\Phi + \Psi)$, and $W(\Psi)$. All the decay angular distributions are given in two photon LAB energies, 1.97 – 2.17 GeV (upper panel) and 2.17 – 2.37 GeV (lower panel). Data is taken from Ref. [10]. The notation is the same as in Fig. 2.

Our best fits with the choice of $J^P = 3/2^-$ to the experimental energy dependence of the differential cross section at forward angle and angular dependence of the differential cross section [10, 17] are shown in Figs. 2 and 3, respectively. The dotted, dashed, and solid lines correspond to contributions from nonresonant, *i.e.*, Pomeron plus (π, η) -exchange, resonant, and the full results, respectively. We find that no matter how the Pomeron parameters are varied, it is not possible to describe the nonmonotonic behavior of the differential cross section at forward direction as a function of photon energy with only the nonresonant contribution. One also sees from Fig. 3 that the addition of a resonance markedly improves the agreement with the data on angular dependence.

Our results for the decay angular distributions of the ϕ -meson in its rest frame (or the Gottfried-Jackson system, hereafter, called GJ-frame), which can be expressed in terms of the spin-density matrix elements ρ_{ij}^α [8, 24], are shown in Fig. 4, where the contributions from nonresonant, resonant, and the full results are again denoted by dotted, dashed, and

Table 1: The results for N^* parameters with $J^P = 3/2^-$.

$M_{N^*}(\text{GeV})$	2.10 ± 0.03
$\Gamma_{N^*}(\text{GeV})$	0.465 ± 0.141
$eg_{\gamma NN^*}^{(1)}g_{\phi NN^*}^{(1)}$	-0.186 ± 0.079
$eg_{\gamma NN^*}^{(1)}g_{\phi NN^*}^{(2)}$	-0.015 ± 0.030
$eg_{\gamma NN^*}^{(1)}g_{\phi NN^*}^{(3)}$	-0.02 ± 0.032
$eg_{\gamma NN^*}^{(2)}g_{\phi NN^*}^{(1)}$	-0.212 ± 0.076
$eg_{\gamma NN^*}^{(2)}g_{\phi NN^*}^{(2)}$	-0.017 ± 0.035
$eg_{\gamma NN^*}^{(2)}g_{\phi NN^*}^{(3)}$	-0.025 ± 0.037

solid lines, respectively. We see that the data in $W(\cos\theta)$ at both energies of $E_\gamma = 1.97 - 2.17$ GeV and $2.17 - 2.37$ GeV, $W(\Phi - \Psi)$ at $2.17 - 2.37$ GeV, and $W(\Phi)$ again at $2.17 - 2.37$ GeV can already be described relatively well by the nonresonant contribution only and do not need strong modification from a resonance. However, the rest of the distributions show some discrepancies between nonresonant contribution and experimental data and the inclusion of resonant contribution does help to reduce the discrepancies. This is especially true for $W(\Phi - \Psi)$ at $2.17 - 2.37$ GeV and $W(\Phi)$ at $1.97 - 2.17$ GeV, where the nonresonant contribution does not describe satisfactorily the experimental data. For both $W(\Phi + \Psi)$ and $W(\Psi)$, our model still fail to give adequate agreement with the data which are of rather poor quality with large error bars.

One might be tempted to identify the $3/2^-$ as the $D_{13}(2080)$ as listed in PDG [12]. The coupling constants given Table 1 can be used to calculate the ratio of the helicity amplitudes $A_{1/2}$ and $A_{3/2}$, though not their magnitudes since only the product of the coupling constants for γNN^* and ϕNN^* are determined. We obtain a value of $A_{1/2}/A_{3/2} = 1.16$, while it is -1.18 for $D_{13}(2080)$. Even though their magnitudes are similar, the relative sign is, however, different. For $J^P = 3/2^+$, we find that the value of $A_{1/2}/A_{3/2} = 0.69$, again with positive sign.

Since the resonance proposed here is obtained by fitting to the existing data, a critical check would be to see whether additional data would substantiate our interpretation. Accordingly, we also calculate the predictions of our model with and without the inclusion of the proposed resonance for all the polarization observables [3]. In general, we find that the effects of the resonance are substantial in many of the polarization observables [4]. We show in Figs. 5 our predictions for some of them like the single polarization observables Σ_x, T_y , in the upper panel, and, in the lower panel, the double polarization observables C_{yz}^{BT} and C_{zx}^{BT} at $E_\gamma = 2$ GeV. It is seen that the effects of the proposed resonance are huge in these polarization observables. In the same figure, results that would be obtained if the $3/2^+$ resonance determined in our best fitting is adopted, are also shown by dash-dotted curve. We see that measurements of these polarization observables would help to resolve the question of the parity of the resonance.

From the $\phi - \omega$ mixing, one would expect that a resonance in ϕN channel would also appear in ωN channel. The only question is their relative decay strength. The

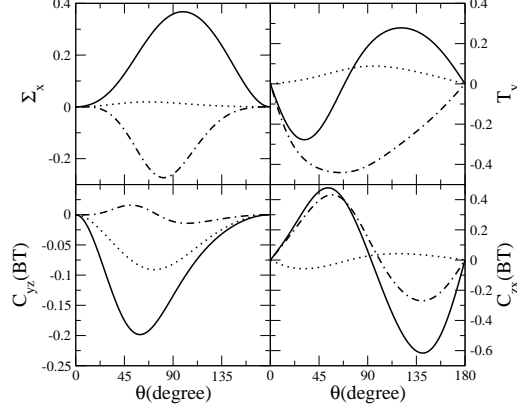


Figure 5: Single and double polarization observables Σ_x , T_y , C_{yz}^{BT} , and C_{zx}^{BT} taken at photon laboratory energy $E_\gamma = 2$ GeV. The solid and dash-dotted lines correspond to our results with the choices of $J^P = 3/2^-$ and $J^P = 3/2^+$, respectively, while the dotted lines denote the nonresonant contribution.

conventional "minimal" parametrization relating ϕNN^* and ωNN^* is

$$g_{\phi NN^*} = -\tan \Delta\theta_V x_{\text{OZI}} g_{\omega NN^*}, \quad (5)$$

with $\Delta\theta_V \simeq 3.7^\circ$ corresponds to the deviation from the ideal $\phi - \omega$ mixing angle. Here, x_{OZI} is called the OZI-evading parameter and the larger value of x_{OZI} would indicate larger strangeness content of the resonance.

In order to study the effects of the resonance postulated here in the ω photoproduction, we adopt the study of Ref. [7] which employs the nucleon resonances predicted by Refs. [25, 26]. In Fig. 6, it is seen that the prediction of their model for the t -dependence of differential cross section at $W = 2.105$ GeV, given in solid lines, still exhibits substantial discrepancy with the most recent experimental data [27] for $|t| > 0.75$ GeV². By adding resonance postulated here to the model of Ref. [23] with $x_{\text{OZI}} = 12$, whose prediction is given in the dashed line in Fig. 6, we see that the differential cross section at $W = 2.105$ GeV can be reproduced with roughly the correct strength. The large value of $x_{\text{OZI}} = 12$ would imply that the resonance we propose here contains a considerable amount of strangeness content.

In summary, we have explored the possibility of accounting for the nonmonotonic behavior as observed by the LEPS collaboration at energies close to threshold as a manifestation of a resonance. We carry out calculations using a model with a nonresonant contribution which consists of Pomeron plus t -channel (π, η) -exchange amplitudes, and a resonant contribution. With resonance mass and width, and coupling constants as parameters, we perform a best fit to all the LEPS data at low energies with possible assignments of $J = 1/2^\pm$ and $J = 3/2^\pm$.

We confirm that nonresonant contribution alone cannot describe the nonmonotonic behavior of the forward differential cross section near threshold and the t -dependence of the differential cross section [9]. We find that the addition of a resonance with $J = 1/2$ of either positive or negative parity cannot explain the local maximum at around $E_\gamma \sim 2.0$

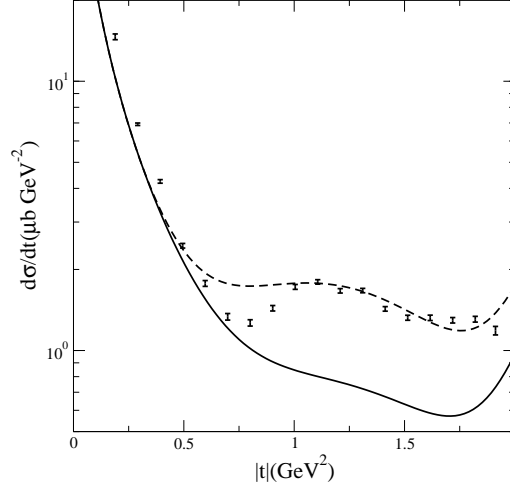


Figure 6: Differential cross section of ω photoproduction as a function of $|t|$ at $W = 2.105$ GeV. Solid and dashed lines represent the model predictions of Ref. [23] without and with the addition of our resonance with $x_{\text{OZI}} = 12$. Data are from Ref. [27].

GeV. However, with an assignment of $J = 3/2$, a nice agreement with most of the LEPS data can be achieved. We prefer the choice of $J = 3/2^-$ as the best fit to the data since its results are more stable with respect to changes in the low-energy Pomeron parameters. The obtained resonance mass and width are 2.10 ± 0.03 and 0.465 ± 0.141 GeV, respectively. The resulting coupling constants give rise to a ratio of the helicity amplitudes $A_{\frac{1}{2}}/A_{\frac{3}{2}} = 1.16$, which differs from that of the known $D_{13}(2080)$ in sign.

Furthermore, we find that the postulated resonance gives substantial contribution to the polarization observables, which can also be used to determine the parity of the resonance if it indeed exists.

The possible effects of this postulated resonance in the ω photoproduction are investigated by incorporating it within a recent calculation [23] for this reaction. It turns out that the addition of our resonance, with a choice of a large value of OZI-evading parameter $x_{\text{OZI}} = 12$, could indeed considerably improve the agreement of the model prediction with the most recent data. That would imply the resonance postulated here does contain considerable amount of strangeness content.

There are a few caveats in our study. The first concerns the low-energy Pomeron parameters which are not presently very precisely determined. If the postulated resonance contains considerable amount of strangeness, then it could couple strongly to, say, $K\Lambda$ channel. Question would then arise on how the coupled-channel effects would modify the low-energy behavior of the nonresonant amplitude employed in this investigation. This can be answered only with a full coupled-channel calculations as carried out in Ref. [15]. Another question is the validity of our assumption to account for the local maximum with just one resonance. As seen in the calculation of the effects of our postulated resonance, some discrepancies with the recent data still persist after the ad-

dition of this resonance. Accordingly, our study may have raised more questions than it answers. Clearly, further studies, both experimentally and theoretically, are needed on the ϕ -meson photoproduction at low energies.

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